WHAT DOES GRAVITY TELL US ABOUT LUNAR CRUSTAL STRUCTURE?
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Clementine and historical tracking data have provided powerful constraints on the lunar gravity field. Using topographic, petrologic, and seismologic constraints, gravity anomalies can be completely attributed to near-surface, crustal thickness and density variations [1,2]. Such non-unique interpretations of gravity rely on assumptions concerning the densities of anorthositic, basaltic, and other crustal components, and the density of a more mafic, higher velocity mantle. Uncertainties in these densities directly affect our estimates of the minimum and maximum crustal thicknesses on the Moon, but uncertainty in the gravity field also hinders our understanding. To quantify this uncertainty, we show interpretations based on recent gravity solutions [3, 4] using combinations of spatial, power-law, and singular-value constraints, and various density assumptions. Our most robust finding is that the mean crustal thickness is 61±3 km, based on a 55 km Apollo 12-14 seismic constraint. This conclusion requires further geophysical confirmation, but is consistent with interpretations of Apollo 16 seismic data. We also find that the lateral crustal structure is highly variable, indicative of spatial variation in melting of the lunar exterior and/or impact-related redistribution. Current lunar gravity models best resolve regional scale crustal structure on the equatorial near side. We cannot unambiguously say whether giant impacts have excavated the lunar "mantle" beneath the centers of nearside basins, but all models require significant uplift of the lunar moho. It is evident that nearly all of the upper crust is removed by these events.

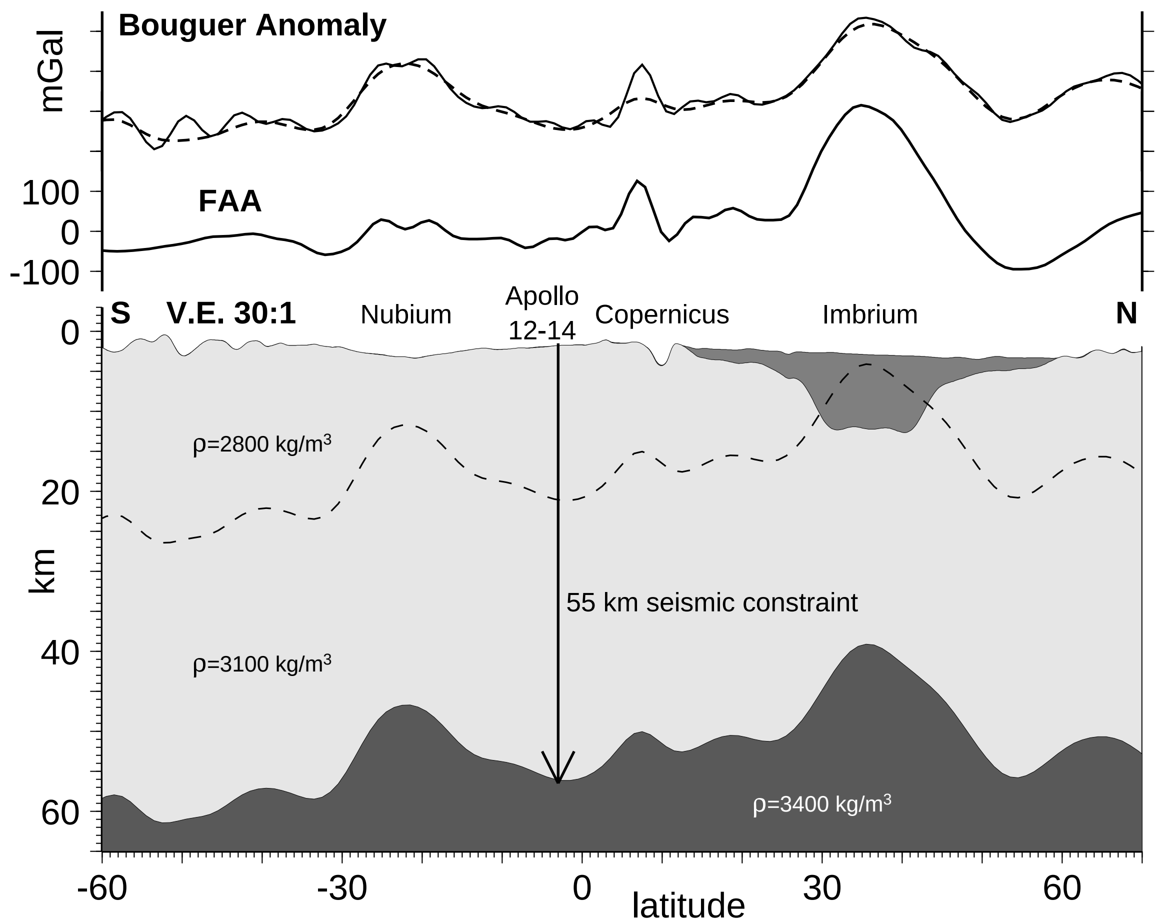

Figure 1. S-N profile at longitude 20°W of crustal structure assuming stratified density [2]. Mare basalt fill [5], with density 3300 kg/m^3, is included in Bouguer correction. A density interface (dashed curve), with an increase to 3100 kg/m^3, is assumed at a global average depth of 25 km. The thickness of the lower crust is assumed constant, implying vanishing upper crust beneath Mare Imbrium. Top: BA (solid) and anomaly predicted by smooth downward continuation (dashes).

Figure 1 shows a globally computed interpretation of the Bouguer anomaly (BA), corrected for up to 10 km of mare basalt fill [1,5]. The free-air anomaly (FAA) is taken from GLGM-2 [3]. The mascon signature of the Nubium and Imbrium basins is visible, but smaller features such as Copernicus crater are not resolved. At the southern end, some of the topography aliases into the BA, despite being smoothed by an upward-continuation filter. The spherical harmonic coefficients of the anomaly are downward continued to a pair of crustal interfaces (light gray region) after being smoothed by a minimum-structure filter [1]. The filter amplitude is 50% at degree l=30, where the formal uncertainty in the gravity coefficients is equal to the degree variance [3]. The resulting model suppresses features smaller than about 360 km wavelength. Thus the predicted anomaly does not match the BA exactly. Note that the constraint of a constant-thickness lower crust cannot be met beneath Imbrium, and the moho uplift is accordingly greater than shown. Downward continuation to a single interface at the moho results in about 2.5 km greater uplift.

Each model is constrained to match a seismic constraint on crustal thickness at the Apollo 12 and 14 sites (arrow). At these stations, velocities increased to mantle values at depths of 55 to 60 km. In either density model, the global, mean crustal thickness is within a few hundred meters of 61 km. Thus the seismologic constraint has a first-order impact on global thickness, while model considerations are second order. Taken together, these uncertainties imply about 3 km uncertainty in crustal thickness.

The gravity models predict minimum thicknesses of about 20 km over Crisium and Orientale, consistent with the lack of mantle exposure by large impacts. The models are also consistent with a tentative finding of a moho at 75 km beneath the Apollo 16 highland site [8], predicting a crustal thickness of 65-67 km in this region.

Figure 2 shows the extent to which the choice of constraints used to reduce orbital tracking data influences the gravity model and the crustal structure. A weaker filter applied to the BA, with half the amplitude at degree 40, resolves wavelengths of 280 km (dotted curve in crust). This model has greater lateral variation in thickness but virtually the same global thickness of 61 km. An earlier study based on preliminary Clementine topography and gravity fields [6] truncated the coefficients at degree 30, obtaining 63 km global thickness. These values imply a lunar crust making up 10-10.5% of the total volume.

The choice of gravity field also affects the global thickness by less than 1 km. Figure 2 shows two alternative fields derived from the reference model, GLGM-2. In both cases, the spectral Kaula constraint is partially relaxed. These fields have greater amplitude and result in somewhat larger variation in crustal thickness. They have sharper resolution of some features, but suffer from the inherent noisiness of the historical tracking data.

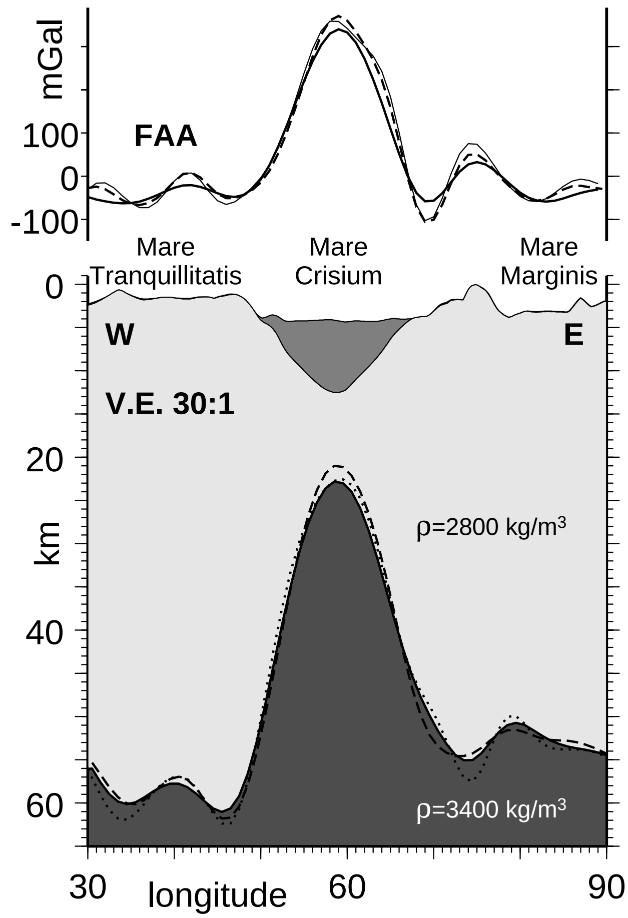

Figure 2. East-west profiles of crustal structure across Mare Crisium, showing the effect of varying the power-law constraint in the gravity solution. The solid curves represent a power-law constrained, reference solution, Goddard Lunar Gravity Model-2 (GLGM-2). Coefficient sigmas at degree l are constrained by Kaula*15 (1 Kaula = $10^{-5}/l^2$). LGM0309E (thin curve) uses the same data with a weaker (Kaula*60) constraint. LGM0309M (dashes) relaxes the spectral constraint used for GLGM-2 in regions over the near side where direct tracking at elevations below 500 km is available.

References: [1] Neumann, G.A. et al., *JGR, 101*, E7, 16,841-16,863, 1996. [2] Wieczorek, M.A., and R.J. Phillips, The Structure and Compensation of the Lunar Highland Crust, submitted to *JGR-Planets*, 1996. [3] F.G. Lemoine et al., GLGM-2: A 70th degree and order lunar gravity model from Clementine and historical data, submitted to *JGR-Planets*, 1995. [4] Lemoine, F.G. et al., *Eos Trans. AGU*, *77*, F152, 1996. [5] Solomon, S. C., and J.W. Head, *Rev. Geophys.*, *18*, 107-141, 1980. [6] Zuber, M.T. et al., *Science*, *266*, 1839-1843, 1994. [7] Smith, D.E. et al., The topography of the Moon from the Clementine LIDAR, *JGR-Planets*, in press, 1997. [8] Goins, N.R., et al., *Geophys. Res. Lett.*, *8*, 29-32, 1981.